ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 37 (2013) 4620 – 4627
Energy Procedia

GHGT-11

Effect of hydraulic fracturing orientation in surface dissolution process

Qing Tao* and Steven L. Bryant

Center for Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, TX 78712, USA

Abstract

Extraction of brine from the aquifer offers advantage during CO_2 storage by greatly mitigating pressure elevation during injection. If the brine is used in the surface dissolution storage process, the position of the CO_2 concentration front when it first touches the saturation pressure contour defines the areal limit of CO_2-saturated brine and hence the aquifer utilization efficiency. Hydraulically fracturing the injectors moves the saturation pressure contour closer to the extractors and increases utilization efficiency. If the fractures are oriented towards extractors, early breakthrough will result and aquifer utilization efficiency will be negatively affected. Conversely fracturing the injectors in the direction perpendicular to injector/extractor flow paths improves the utilization efficiency. The design of a line drive pattern of injection/extraction wells for surface dissolution should therefore account for stress orientation in the storage formation.

Keywords: surface dissolution; aquifer utilization efficiency; hydraulic fracturing; fracture orientation; concentration front

1. Introduction

Extraction of CO_2 from flue gases, compression and injection into a brine-filled structure is the "standard approach" to geologic carbon sequestration. The injected CO_2 is subject to the storage mechanisms of structural containment, dissolution in brine, residual trapping and mineralization in aquifers [1][2]. Since the injected supercritical CO_2 is less dense than resident brine, buoyancy will drive CO_2 to move upward. This migration on one hand could increase residual and dissolution trapping [1],

* Corresponding author. Tel.: +1-512-471-3250; fax: +1-512-471-9605.
E-mail address: qing.tao@utexas.edu.

doi:10.1016/j.egypro.2013.06.370

but on the other hand it may impose serious risks of leakage from storage formation [3][4], and of contamination of ground water [5][6].

One way to eliminate the risks associated with buoyancy-driven flow is the "surface dissolution" storage strategy [7]. The process involves lifting brine from one region of the target formation through extraction wells, dissolving the CO_2 stream in the extracted brine in a mixing tank and then injecting the CO_2-saturated brine into another region of the target formation (Fig. 1). The extraction offers advantages over the standard approach including greatly reducing the brine displacement and significantly decreasing the elevated pressure near the injectors. Although surface dissolution requires large volume of brine, the power requirement for pumping and mixing is manageable [7].

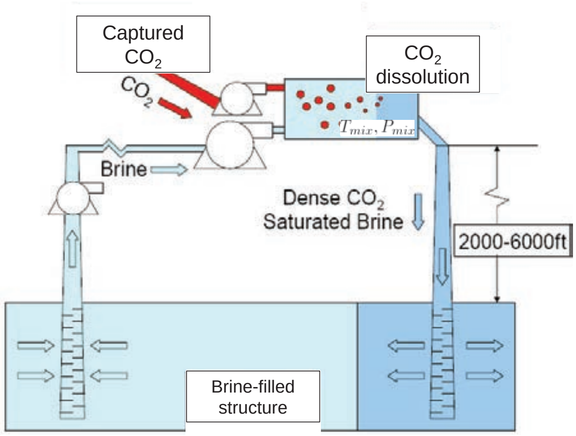

Fig.1. Schematic of the surface dissolution process. The captured CO_2 stream mixes with the extracted brine at the surface and then the saturated brine is re-injected into the brine-filled structure [7].

Further work on surface dissolution process involves the search for an optimal design of the injection/extraction strategy. Jain and Bryant [8] identified the constraint imposed by the pressure field in the storage formation during injection period as a main parameter controlling the design. An analytical solution was derived to optimize well count and placement, required formation volume and storage footprint (areal extent of CO_2) for an ideal aquifer. Tao and Bryant [9] investigated the effect of heterogeneity on aquifer utilization efficiency and provided an optimal control strategy of injection/extraction rates to improve the utilization efficiency. They further proposed an optimal well pattern orientation strategy by placing line-drive injectors in high permeability zone and extractors in low permeability zone, so that the saturation pressure contour is closer to the extractors and thus increases the aquifer utilization efficiency.

A corollary to the effect of well pattern orientation is that hydraulically fracturing the injectors also moves the saturation pressure contour towards extractors. This is because in effect the well stimulation creates a high permeability zone near the injectors. However if the fractures extend from the injectors towards extractors, injected brine will arrive early at the saturation pressure contour, and aquifer utilization efficiency will be correspondingly reduced. In this study we investigate the impact of the orientation of fractures and provide guidelines on utilizing hydraulic fracturing to improve aquifer utilization efficiency.

2. Effect of Fracture Orientation

The aquifer utilization efficiency (E_a) is defined as the fraction of pore volume swept when the CO_2 saturated brine reaches the saturation pressure contour in the aquifer. The surface dissolution process involves only single-phase (aqueous) flow, so the multiphase flow and gravity effects that reduce sweep efficiency in the standard approach are negligible. The swept fraction depends primarily on well pattern and reservoir heterogeneity. The injection of CO_2-saturated brine drives a concentration front towards the extractors, and at time T_{arrive} it just reaches the saturation pressure contour. (The front is not sharp because of hydrodynamic dispersion, so in practice the arrival time is defined with respect to a particular concentration, e.g. $0.05C_{inj}$.) The shape of the concentration front at T_{arrive} defines the maximum areal extent of CO_2-saturated brine and corresponding E_a for a process intended to store CO_2 entirely in the aqueous phase.

High permeability zones near injectors are beneficial to a surface dissolution project as they shift the saturation pressure contour towards the extractors and thus increase the aquifer utilization efficiency. One way to create these high permeability zones is to hydraulically fracture the injectors [10][11][12]. The orientation of the fractures is perpendicular to the direction of minimum principal stress. For typical storage formations, the fractures will be vertical. The direction of the fractures provides preferential pathways for flow in the permeable layers. Here we consider two limiting cases: the direction of the fractures is oriented perpendicular to or parallel to injector/extractor flow paths.

To isolate the effect of orientation, we assume the storage formation is an ideal (homogeneous) aquifer (Fig. 2a). In a surface dissolution project this corresponds to the best scenario in terms of aquifer utilization efficiency because it eliminates early arrival of the concentration front along paths connecting regions of relatively large permeability [13]. This storage aquifer is assumed to contain formation brine only. A line-drive pattern is deployed which consists of four injectors on the west side and four extractors on the east side.

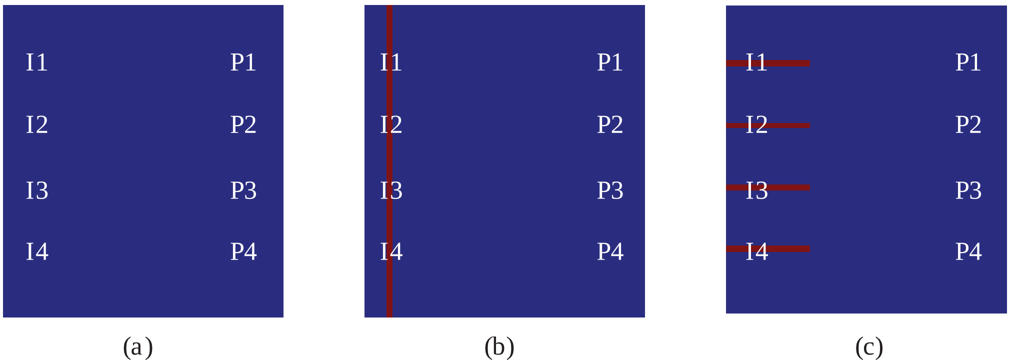

Fig. 2. (a) base case – unfractured wells in homogeneous aquifer; (b) hydraulically fractured injectors oriented perpendicular to injector/extractor flow paths; (c) as (b) but oriented towards extractors. For (b) and (c), the fractures are represented in flow simulations as segments of horizontal wells (red lines) perforated in the plane of the schematic.

The hydraulic fracturing is conducted in the four injectors. To account for the effect of hydraulically fractured wells on the flow field, researchers have proposed to use horizontal wells perforated in a horizontal direction (i.e. transverse to orientation of fracture) to represent the fracture surfaces/lines in reservoir simulation [14][15][16]. This approach has been proved to be effective and thus we use it in this study.

The storage aquifer in Fig. 2 is discretized into a 50 × 50 domain. The size of each grid block is 40 ft per edge. The rock matrix permeability is 1 md. Assume a typical fracture of 400 ft length is created at each injector. It extends a distance in the direction of fracture for 10 grid blocks (Fig. 2b and 2c). The fractures are represented using horizontal well segments that are perforated in respective directions. We will then investigate how the fracture direction affects the flow of CO_2-saturated brine in the aquifer and the corresponding aquifer utilization efficiency at $T=T_{arrive}$.

The reservoir simulation is conducted using a compositional reservoir simulator. The four injectors and extractors are under bottom-hole pressure (BHP) control. The BHPs for the injectors are the same, and likewise the extractors are set to same BHP. The control pressures do not change with time. BHP control for the injectors is chosen so that the effect on the pressure field can be compared in a consistent manner. Larger injection rates are of course achieved for the fractured wells. This affects the value of T_{arrive} but the rate does not affect the volume of fluid injected when the concentration front reaches the saturation pressure contour. Thus the utilization efficiencies for the three cases can be compared directly. The aquifer has a closed boundary (no flow at boundary cells). We illustrate the pressure contours and CO_2 concentration contours by running the simulation for sufficient time.

The pressure contours (Fig. 3) show a decline of pressure from the injectors towards the extractors (800 psi difference). In the homogeneous aquifer with four vertical injectors (Fig. 2a), the pressure draws down quickly from the injectors towards the extractors (Fig. 3a). In the cases that the injectors are hydraulically fractured (Figs. 2b and 2c), the contours of larger injection pressure extend farther from the injectors (Fig. 3b and 3c).

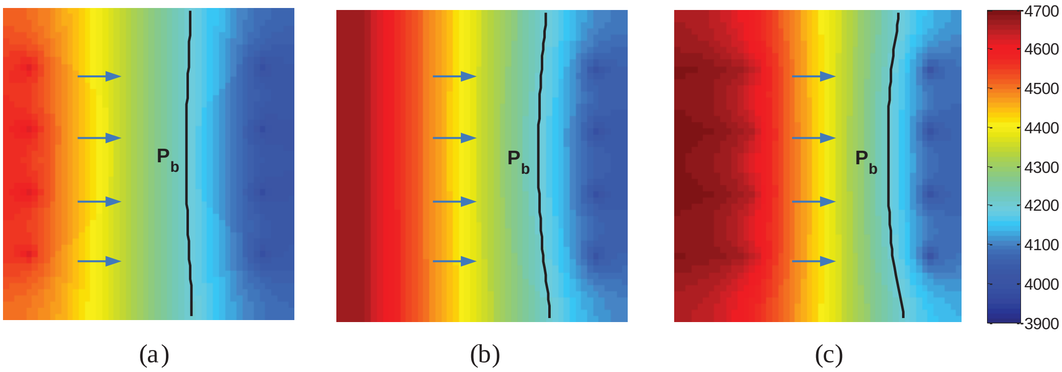

Fig. 3. Pressure fields (in psi) corresponding to the three scenarios in Fig. 2. Arrows represent the flow paths (from injectors towards extractors). Injection through hydraulically fractured wells moves the fluid pressure contours further away from the injectors, in the direction of the fractures. Correspondingly the saturation pressure (P_b) moves towards the extractors, increasing the aquifer utilization efficiency.

The saturation pressure P_b can be optimized [17] and in this work it is pre-determined to be 4200 psi (black curve in Fig. 3). The locations of the P_b contour for the three cases of Fig. 3 are plotted together in Fig. 4. It shows that hydraulically fracturing the injectors has moved the saturation pressure contour a notable distance towards the extractors. In the case that the fractures are in the direction perpendicular to flow paths (Fig. 3b and Frac-P in Fig. 4), the saturation pressure contour occurs four grid block nearer the extractors compared with the base case. In the case that the fractures are in the direction same as flow paths (Fig. 3c and Frac-S in Fig. 4), the saturation pressure contour occurs even further away, seven grid blocks distant from the base case.

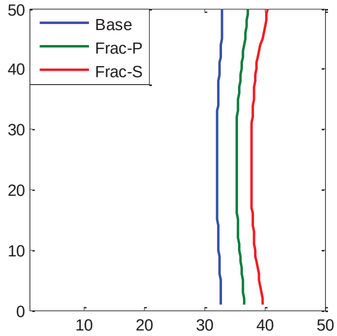

Fig. 4. Comparison of locations of saturation pressure in the three scenarios of Fig. 3. The saturation pressure is pre-determined to be 4200 psi. The axes are the grid block numbers in *x* (same direction as flow paths) and *y* (perpendicular to flow paths) directions. Hydraulic fracturing the injectors perpendicular to flow paths (Frac-P) moves the saturation pressure towards extractors by four grid block distance from the base case. Hydraulic fracturing in the direction same as flow paths (Frac-S) moves the saturation pressure contour even further, by seven grid block distance from the base case.

The relative locations of the saturation pressure contours suggest that fractures oriented toward the extractors are optimal. However the utilization efficiency depends not just on the contour location but on how much CO_2 saturated brine has been injected when the concentration front reaches the contour. The concentration contours after 0.24 pore volume (PV) injected (Fig. 5) describe the direction and speed of the CO_2-saturated brine movement in the aquifer. The concentrations are high near injectors and decrease towards extractors (zero concentration corresponds to native brine). The comparison between the three scenarios shows that hydraulically fracturing the injectors in the direction perpendicular to flow paths spreads the concentration contours much wider in the direction transverse to injector/extractor flow paths (Fig. 5b, cf. Fig. 5a). This greatly improves the sweep efficiency and thus is beneficial to the aquifer utilization efficiency. Hydraulically fracturing the injectors in the direction same as flow paths gives the concentration contours a “head start”, enabling them (Fig. 5c, cf. Fig. 5a) to arrive at the saturation pressure contour when less brine has been injected. This results in early termination of the surface dissolution project if ex-solution of a CO_2 gas phase is to be avoided.

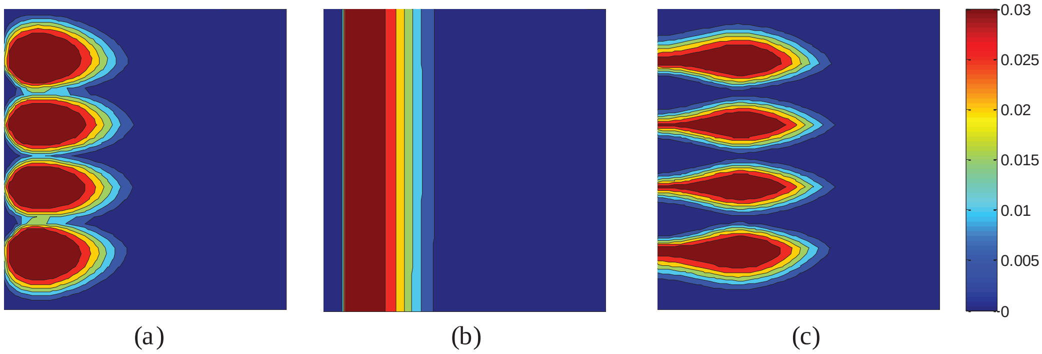

Fig. 5. CO_2 concentration contours (mole fraction) in the three scenarios in Fig. 2 after 0.24 PV of CO_2-saturated brine has been injected. The concentration front is defined as the contour of 5% of the injected concentration of dissolved CO_2. (a) ideal, homogeneous aquifer (base case); (b) hydraulically fracturing the injectors in the direction perpendicular to flow paths spreads the concentration contours wider and hence improves the sweep efficiency; (c) hydraulic fracturing in the direction same as flow paths reduces the distance between the injectors and the extractors, reducing the sweep efficiency.

To quantify the comparison between the three scenarios, we calculate the arrival time of concentration front at the saturation pressure (T_{arrive}) and the corresponding aquifer utilization efficiency (E_a). The concentration front is assumed to be the contour of 0.1% mole fraction of CO_2, which corresponds to 5% of the injected concentration.

Figure. 6 illustrates the situation when the concentration front just reaches the saturation pressure contour (T=T_{arrive}). The position of the concentration front at T_{arrive} defines the maximum aquifer utilization efficiency (E_a). Comparing the three scenarios, hydraulically fracturing the injectors in the direction perpendicular to flow paths not only moves the saturation pressure contour towards the extractors, but also spreads the concentration front much wider which improves the sweep efficiency (cf. Fig. 6b to Fig. 6a). As a result, it has delayed T_{arrive} by 380 days and increased E_a by 16.7% of aquifer pore volume (Table 1, cf. T_{arrive} = 3775 days and E_a = 71.2%, to T_{arrive} = 3395 days and E_a = 54.5% in base case). This is a significant improvement and thus is desirable in surface dissolution projects.

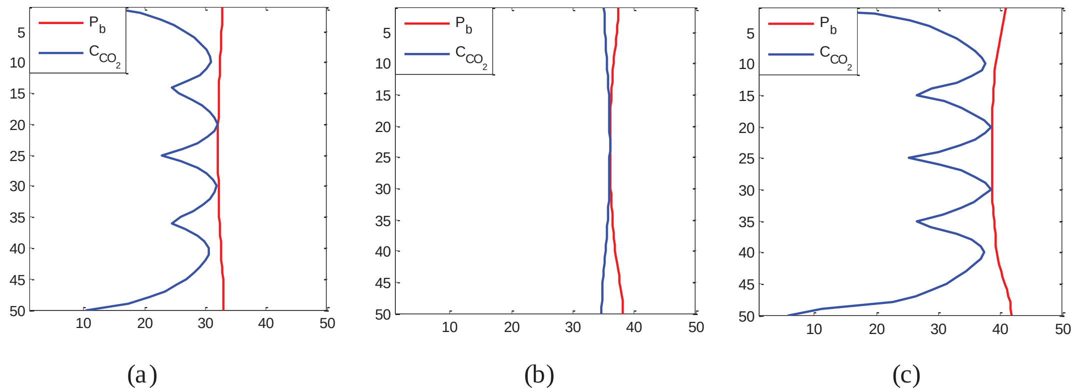

Fig. 6. CO_2 concentration front (blue curve, cf. the concentration contours in Fig. 4) just reaches the saturation contour (red curve, cf. the pressure contours in Fig. 3) in the three scenarios. The arrival time T_{arrive} and aquifer utilization efficiency E_a are estimated and summarized in Table 1.

Table 1. Comparison of T_{arrive} and E_a at T=T_{arrive} for the three scenarios in Fig. 6.

	Base Case	Hydraulic fracturing injectors (perpendicular to flow paths)	Hydraulic fracturing injectors (same as flow paths)
T_{arrive} (days)	3395	3775	2085
E_a (%)	54.5	71.2	62.5

On the other hand, although hydraulically fracturing the injectors in the direction same as flow paths has moved the saturation pressure closer to the extractors by a large distance, the travel distance between injectors and extractors is also smaller. Thus saturated brine arrives at the saturation pressure contour earlier, and hence with a smaller areal sweep (Fig. 6c). This results in a significant decrease in T_{arrive} by 1300 days from base case (Table 1, cf. T_{arrive} = 2085 days to 3395 days in base case), yet still increases E_a by 8% of aquifer pore volume (cf. E_a = 62.5% to 54.5% in base case). Despite its small increase in aquifer utilization efficiency, this orientation of fractures is not recommended as it shortens the life time of a surface dissolution project.

3. Discussion

This example shows that stimulating injection wells with hydraulic fractures increases utilization efficiency when the fracture lengths are a significant fraction (here about 1/4) of the separation between the lines of injectors and extractors. Clearly the same effect could be obtained with horizontal wells. This would be advantageous if other constraints made it difficult to orient the lines of injection/extraction wells for the optimal hydraulic fracture orientation. By optimizing the length of the horizontal wells the operator could also tailor the alteration of the flow field in a manner that would be more difficult to achieve with fracture stimulation. The tradeoffs involve the greater cost of horizontal well construction and the need to ensure hydraulic fractures are contained within the storage formation. Long experience in the oil and gas industry makes fracture containment achievable. It should be noted that for surface dissolution, the probability of buoyancy-driven leakage is minimal, and thus the risk associated with fracturing should be much less than for the standard approach to storage.

The benefit of suitably oriented hydraulic fractures was quantified here for a homogeneous formation. The effect of permeability heterogeneity is to create preferential flow paths between injectors and extractors, with corresponding reduction in E_a relative to the homogeneous case. It is possible to optimize the distribution of injection and extraction rates among the wells to overcome this effect [9]. A similar procedure could be applied here. Indeed, a more general optimization could readily be conducted which would involve several design variables: which injection wells to stimulate (or drill as horizontals), the control schedule for injectors, and the control schedule for the extractors.

4. Conclusions

Stimulating injection wells by hydraulic fracturing can significantly increase the aquifer utilization efficiency for the surface dissolution approach to GCS. The orientation of the fractures relative to the orientation of injector/extractor flow paths is important. We illustrate by simulating the result of hydraulically fracturing the injectors in two limiting cases. Hydraulic fractures oriented perpendicular to injector/extractor flow paths significantly increases the aquifer utilization efficiency, by improving the sweep efficiency and by moving saturation pressure contour towards extractors. On the other hand, hydraulically fracturing the injectors in the direction same as flow paths moves the saturation pressure contour even closer to the extractors, but also reduces the travel distance between injectors and extractors. The latter effect reduces the benefit of the former. Utilization efficiency increases relative to the unstimulated case, but the life time of the project is reduced. The design of a line drive pattern of injection/extraction wells for surface dissolution should therefore account for stress directions in the storage formation. If this is done, then hydraulic fracturing or construction of horizontal wells will increase storage efficiency appreciably.

Acknowledgements

This work was supported by Center for Frontiers of Subsurface Energy Security (an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0001114), and by the Geologic CO_2 Storage Joint Industry Project at UT-Austin.

References

[1] Ennis-King, J. and Paterson, L., 2002. Engineering Aspects of Geological Sequestration of Carbon Dioxide. SPE Asia Pacific Oil and Gas Conference and Exhibition, Melbourne, Australia, 8–10 October, SPE-77809-MS.
[2] Kumar, A., Ozah, R., Noh, M., Pope, G.A., Bryant, S., Sepehrnoori, K., and Lake, L.W., 2005. Reservoir Simulation of CO_2 Storage in Deep Saline Aquifers. SPE Journal, 10 (3): 336–348.
[3] Pruess, K., 2004. Numerical simulation of CO_2 leakage from a geologic disposal reservoir, including transitions from super- to sub-critical conditions, and boiling of liquid CO_2. SPE Journal, 9, 237–248.
[4] Tao, Q., Checkai, D.A., Huerta, N.J. and Bryant, S.L., 2010. Model to Predict CO_2 Leakage Rates Along a Wellbore. SPE Annual Technical Conference and Exhibition, Florence, Italy, 20-22 September, SPE-135483-MS.
[5] Nicot, J.P., 2008. Evaluation of large-scale CO_2 storage on fresh-water sections of aquifers: An example from the Texas Gulf Coast Basin. International Journal of Greenhouse Gas Control, 2(4): 982-593.
[6] Benson, S.M., R. Hepple, J. Apps, C. F. Tsang, and M. Lippmann., 2007. Lessons Learned from Natural and Industrial Anologues for Storage of CO_2 in Deep Geological Formations. Lawrence Berkeley National Laboratory report LBNL-51170.
[7] Burton, M. and Bryant, S., 2009. Eliminating Buoyant Migration of Sequestered CO_2 Through Surface Dissolution: Implementation Costs and Technical Challenges. SPE Reservoir Engineering and Evaluation, 12: 399-407.
[8] Jain, L. and Bryant, S.L., 2011. Optimal design of injection/extraction wells for the surface dissolution CO_2 storage strategy. Energy Procedia, 4: 4299–4306.
[9] Tao, Q. and Bryant, S.L., 2012. Optimal control of injection/extraction wells for the surface dissolution CO_2 storage strategy. Carbon Management Technology Conference, Orlando, Florida, USA, 7-9 February, SPE-151370-MS.
[10] McGuire, W.J. and Sikora, V.J., 1960. The effect of vertical fractures on well productivity. Journal of Petroleum Technology, 12 (10): 72-74.
[11] Prats, M., 1961. Effect of vertical fractures on reservoir behavior – incompressible fluid case. SPE Journal, 1 (2): 105-118.
[12] Gadde, P.B. and Sharma, M.M., 2001. Growing injection well fractures and their impact on waterflood performance. SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 30 September-3 October, SPE-71614-MS.
[13] Tao, Q., 2012. Modeling CO_2 Leakage from Geological Storage Formation and Reducing the Associated Risk. Ph.D. Dissertation, The University of Texas at Austin.
[14] Thomas, L.K., Chin, L.Y., Pierson, R.G. and Sylte, J.E., 2003. Coupled geomechanics and reservoir simulation. SPE Journal, 8 (4): 350-358.
[15] Cipolla, C.L., 2009. Modeling production and evaluating fracture performance in unconventional gas reservoirs. Journal of Petroleum Technology, 61 (9): 84-90.
[16] Cipolla, C.L., Lolon, E.P., Erdle, J.C. and Rubin, B., 2010. Reservoir modeling in shale-gas reservoirs. SPE Reservoir Evaluation & Engineering, 13 (4): 638-653.
[17] Jain, L., 2010. Factors Determining Rapid and Efficient Geologic Storage of CO_2. M.S. Thesis, University of Texas at Austin.